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MEASUREMENTS OF LOAD TRANSMISSION THROUGH GROUNDED ICE RUBBLE

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ABSTRACT:

During the winter of 1986/87 a full scale field study of ice rubble was conducted at ESSO's CRI (Caisson Retained Island) at a drilling location in the Beaufort Sea. The aim was to obtain ice rubble characteristics and load transmission data so that a theoretical model could be developed, and this paper summarizes the collected field data.

Data was collected from stress sensors on the caissons, pressure panels in the rubble, pressure sensors in the sea ice, strain rosettes, thermocouple arrays, movement surveys, and rubble profile surveys. Local pressures of 4 MPa were measured at the CRI during initial rubble formation but by late winter the surrounding grounded rubble had reduced the contact pressures to negligible values. The thermocouple array data showed that the rubble refrozen layer thickness can exceed 3 m with growth rates in excess of 1.5 cm/day. Northward movement of the landfast sea ice produced pressure against the rubble, reaching a peak average of 360 kPa and survey data indicates a generally northward deformation of the entire rubble field.

1.0 INTRODUCTION

The movement of sea ice against a wide structure, such as an artificial island, produces piles of broken ice called ice rubble. If such piles become sufficiently firmly grounded, subsequent movements will not dislodge them, and a grounded ice rubble field will form. Artificial islands in the Beaufort Sea often become surrounded by such rubble fields and experience

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shows that the rubble fields tend to protect structures from subsequent ice loads. This behaviour might be used to advantage in the design and operation of offshore structures but a thorough understanding of load transmission through grounded ice rubble is first required. To date, some full scale data is publicly available (Nelson et al, 1976; Strilchuk, 1977; K.R. Croasdale and Associates, 1985) but much of the work done is proprietary.

During the winter of 1986/87 a collaborative, full scale, field measurement program was undertaken at ESSO's CRI (Caisson Retained Island) at Kaubvik. The objective was to collect full scale rubble field data that could be used to analytically model force transmission through grounded rubble. Such data was collected and is presented here in summarised form.

2.0 SITE DESCRIPTION

Kaubvik is located in the southern Beaufort Sea, 120 km northwest of Tuktoyaktuk, at the 18 m depth contour. The nearest land is Pelly Island some 26 km to the south. The sea ice usually grows to 2 m thick by the middle of May (Parker, 1987) but when cored on April 10th 1987, it was only 1.5 m thick, implying an end of winter ice thickness of about 165 cm. Historically, Kaubvik is within the landfast ice margin (Markham, 1982) and during the winter of 1986/87 Kaubvik became landfast by the second week in January. The rubble field that formed prior to this was substantial (see fig 5) and did not grow significantly during the remainder of the winter.

The CRI itself is octagonal with eight steel caissons retaining a central sand core. As the water depth was greater than 9 m, a circular, underwater, berm with a design slope of 12:1 was constructed to support the caissons. The caissons have steeply sloping sides, and at the waterline the island diameter is 112 m "across the flats".

3.0 LANDFAST ICE PRESSURE

On behalf of G-CORE, R. Duckworth of B.P. International Ltd installed three pressure sensor rosettes in the level sea ice 180 m southeast of the CRI. Each rosette contained three 7.5 cm diam, mercury filled pressure sensors (see Duckworth et al, 1988), frozen into the ice at a depth of 0.6 m (approximate neutral axis). The stress measured by each sensor was recorded on a data logger every 2 minutes over a one month period. The highest recorded stress was 550 kPa and the largest calculated principal stress was 570 kPa (same event). One sensor in each of the rosettes was oriented to measure stress approximately in the direction of sea ice expansion and in

all cases these sensors gave the largest pressure readings. An intermittent fault with the data logger resulted in the loss of some of the data, leaving 168,000 valid stress readings. The data loss prevents the three principal stresses from being averaged over the entire month but such averaging can be done with the three sensors oriented in the direction of ice expansion (see fig 1). This is expected to be within 85% of the average principal stress

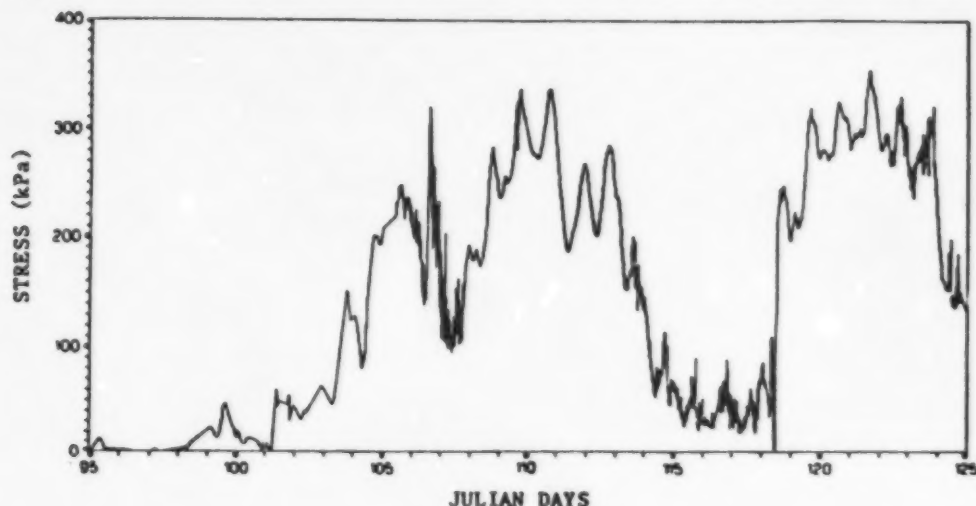


Fig 1. Pressure averaged from three sensors oriented along the line of sea ice expansion. Plot covers entire data collection period.

and from this three important characteristics are apparent:

- The pressure fluctuates daily as a result of daily temperature cycling. In each rosette the sensor oriented in the direction of thermal expansion consistently measured by far the largest pressures, indicating that these stresses represent actual rubble field loading, not biaxial thermal stresses.
- Although most of the time the pressure changes were gradual, on occasion all the sensors indicated, rapid fluctuations of up to 200 kPa. The rapid pressure fluctuations are reminiscent of brittle failure but they occur at pressures well below the usual ductile to brittle transition range (1.5 MPa, Sanderson, 1984). It is expected that this is a result of vertical ice sheet displacement and/or cracking near the rubble field edge.
- An "event" occurs between days 114 and 118.5, and on day 123.5, at which times the pressure drops to a low level. Analysis of sea ice temperature at a depth of 0.6 m shows that this corresponds to periods of minimal thermal expansion of the ice sheet.

4.0 RUBBLE PRESSURE DISTRIBUTION

In January, four pressure panel arrays containing a total of 14 panels were installed in the rubble. The panels were placed within the refrozen layer and panels from three sources were used, 0.5 x 2.1 m Exxon panels, 1 x 1 m and 1 x 2 m Ideal panels, and 0.46 m diameter Arctec panels. They were all of the flat, strain gauge type with width to thickness ratios from 11.5:1 to 40:1. Data collection rates varied between arrays, with data being recorded at 10, 15, and 30 minute intervals.

Several pressure "events" were detected and one of the most significant of these happened one day after installation of the North-west Exxon array. A rubble building event occurred in which new rubble overtopped existing rubble and covered Exxon panels #3 and #4 with piles up to 5 m high. The stresses measured by the NW Exxon panels are shown in fig 2, where panels #1, #2, #3 and #4 were 15, 10, 20 and 35 m away from the rubble field edge respectively. During this event panels on the NW caisson were protected by

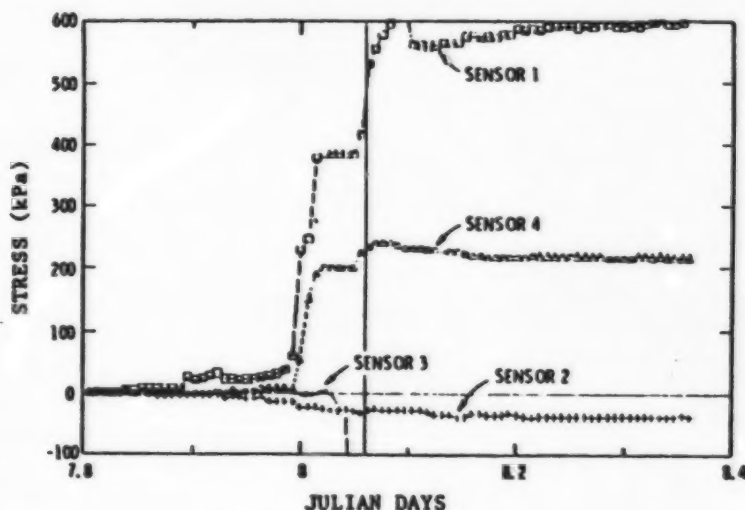


Fig 2. Stress panel output from the North-west Exxon array during a rubble building event.

substantial rubble accumulations but a shearbar panel on the west caisson measured peak pressures up to 40 kPa through rubble accumulations 50 m wide.

Unfortunately, difficulties with calibrating some of the panels within the rubble, and damage to some of the strain gauged elements within the panels, limits the accuracy of the stress data to $\pm 50\%$. All the panels showed generally low stresses, but the limit on data accuracy prevents reliable assessment of the spatial stress distributions within the rubble.

9.0 CRI ICE PRESSURES

The CRI consists of 8, water ballasted, steel caissons arranged in a ring and held together by tensioned wire ropes. The central core of the island is filled with sand which provides the working surface for drilling, as well as sliding resistance against ice forces. Each caisson is equipped with various sensors including two types of external ice pressure sensor. The design global ice pressure is 1.7 MPa (2 m thick ice) and the design local pressure is 4.8 MPa. The ice pressure sensors are two different sizes, 0.165 m diameter "Microcells" (27 operational) and 0.5 m x 2.1 m "Shearbars" (5 operational). Each shearbar panel thus has 50 times the area of a microcell and both types of sensor measure averaged pressure normal to

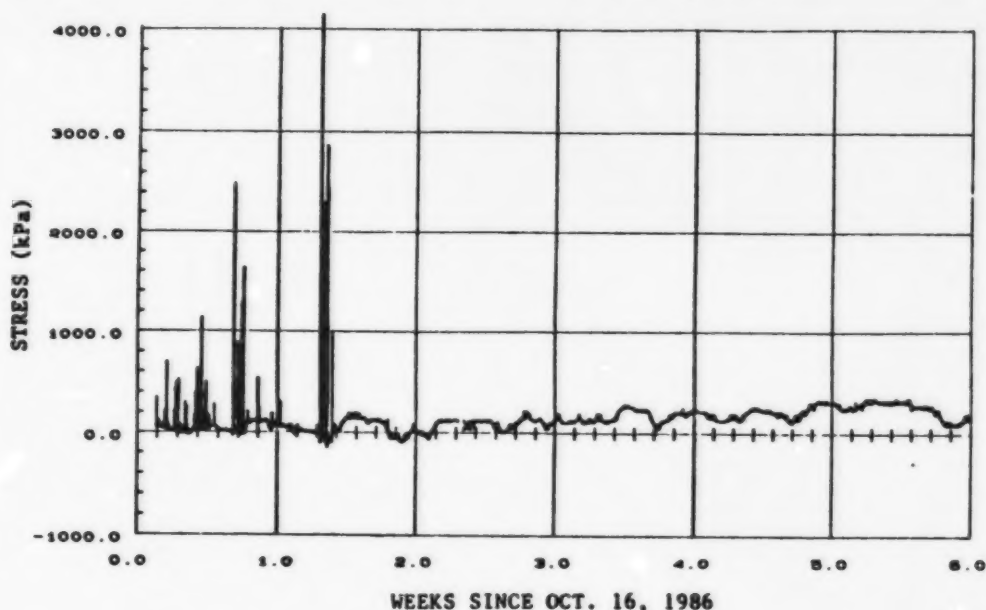


Fig 3 Microcell peak pressure data including the maximum recorded (4.1 MPa). After October 27 the sensor was protected by rubble.

the caisson wall (see figs 3 and 4). Various geotechnical sensors were also installed but they did not detect any soil response to ice loading events.

Until January, the sensors were scanned at a minimum rate of 6 times per minute with the calculated 5 minute average, variance, and peak pressures being recorded. After shut down of operations in mid January, a remote logging system was used which recorded raw data at a constant rate.

The maximum microcell pressure was 4.1 MPa and the maximum shearbar pressure was 0.5 MPa. Both were measured at the Northwest Caisson but

because of the difference in sensor size, the peak microcell pressure was almost an order of magnitude larger than the peak shearbar pressure. Despite this, the time averaged data from both types of sensor should yield similar pressures. The ice loading followed the typical progression from thin ice acting directly against the caissons, to rubble formation which protected the CRI from later ice loads. In the early winter, based on shearbar panel readings, the maximum average force is estimated to be about 100 kN/m which corresponds to a global load of 1200 tonnes. Later in the winter the loads registered on the caissons were negligible, implying almost complete protection by the grounded rubble.

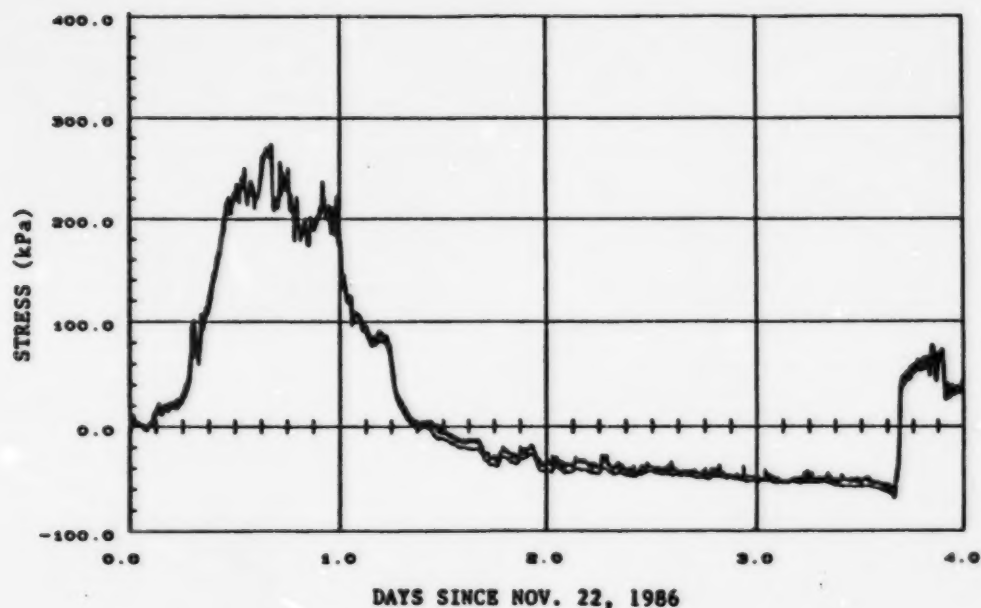


Fig 4 Shearbar panel pressures, the upper line is the peak pressure and the lower line is the 5 minute average. The two "events" shown are not so clear in the less sensitive microcell data (see fig 3).

6.0 RUBBLE MOVEMENT SURVEY

During the January field trip, 15 survey posts were installed at various locations on the rubble. During the January and April field trips the position and elevation of the posts was surveyed from the caissons using an electronic distance measuring instrument (EDM) and a theodolite. Over the measurement period, the rubble at all surveyed locations settled, up to a maximum of 0.45 m, and horizontal movements of up to 0.35 m were measured

(see fig 5). At most locations the generally northward movement is; in the direction of sea ice expansion, away from the CRI, and down the berm slope. The survey posts were usually on top of rubble sails so that tilting of the sails may have contributed up to 0.1 m of the measured horizontal displacements.

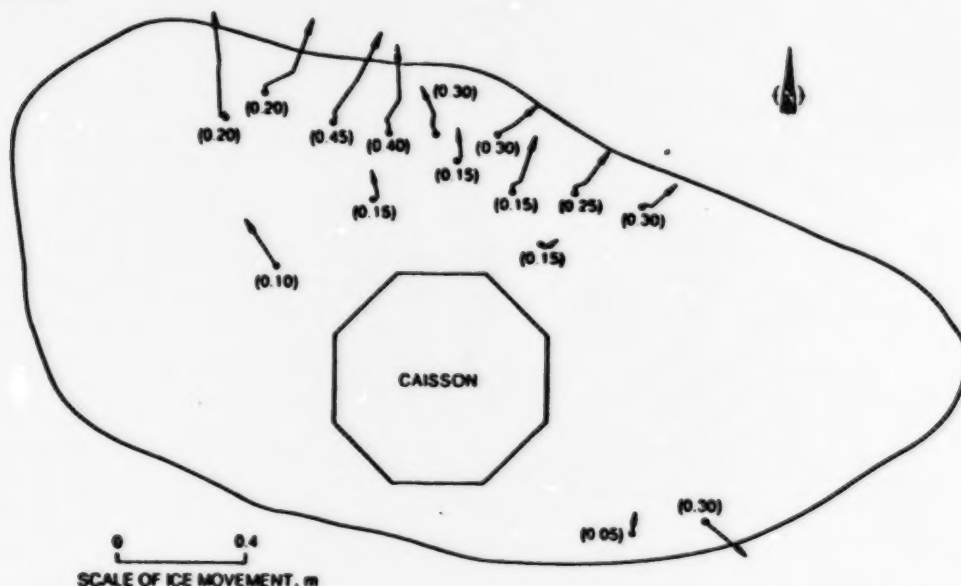


Fig 5 Results of movement survey showing locations of survey posts within the rubble field, measured horizontal movements and (in brackets) the measured settlements.

7.0 ICE RUBBLE STRAINS

In early March 1986, a strain array was installed in a valley, 125 m south-east of the CRI centre. The site was a patch of level ice that formed as a result of sea water flooding behind the outer sail (ie. at sea level). The short thermocouple array was located nearby, and at installation, the refrozen layer was 2.7 m thick. The strain array consisted of 6 LVDT's (linear variable differential transformers) that measured relative movement between 4 posts in the ice surface. The posts were arranged to form the apexes of an equilateral triangle (30 cm apart) with a fourth post in the middle. The centre post held 3 LVDT's, each outer post held 1 LVDT, and over the 51 day field period, 7300 hourly strain measurements were recorded.

The array has been treated as two delta rosettes. One rosette containing the outer three LVDT's and the other containing the inner three LVDT's. The principal strains were calculated with the following result;

- The magnitude of the inner rosette strains was about twice that of the outer rosettes.
- The largest principal strains were tensile with a slope change that corresponds to a drop in sea ice pressure between days 114 and 118.
- The smallest principal "strains" correlate with surface ice temperature and appear to be due to thermal expansion and contraction of the ice.

The discrepancy between the output of the inner and outer rosettes is not understood, but in both cases large tensile strains are recorded. Because of the viscous nature of ice and the differences in strain magnitudes, it is difficult to calculate the level of stress in the ice from the strain data. The trends, however, are the same for both rosettes. A positive slope indicates a compressive stress, and a negative slope indicates a tensile stress. It is thus apparent that during the period of low sea ice pressure between days 114 and 118 (see fig 1), the surface ice at the array was subject to compressive stress (see fig 6). When sea ice pressure resumed on day 118, the stress again became tensile. This was not expected and may have resulted from the effects of a nearby crack or from some form of refrozen layer bending.

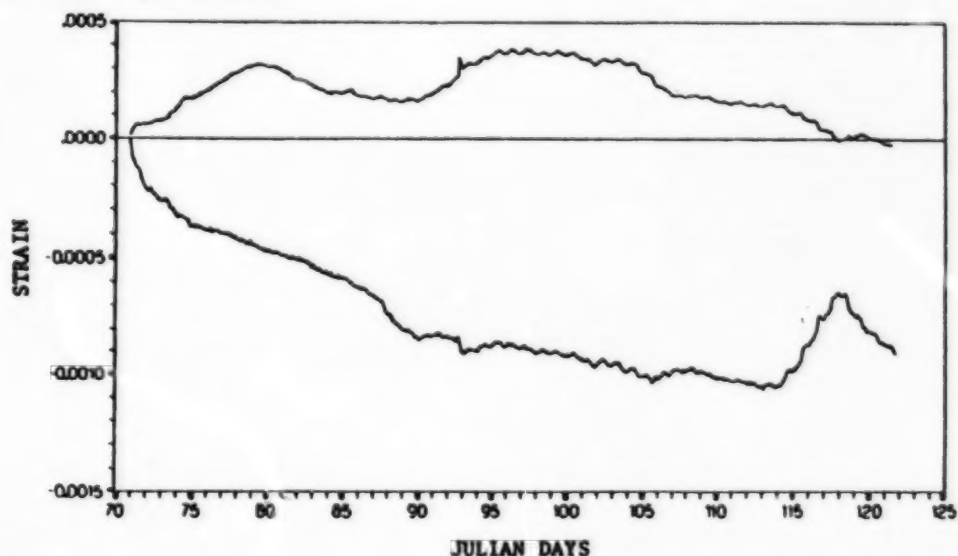


Fig 6 Maximum (positive) and minimum (negative) principal strains measured by the outer rosettes.

8.0 ICE RUBBLE TEMPERATURES

On March 11, two thermocouple arrays were installed in the ice rubble near the strain array. A 12 m array in a rubble sail measured temperatures at 14

elevations, and a 3 m array in a valley measured temperatures at 13 elevations. Over a 51 day period 33,000 hourly temperature measurements were recorded and both arrays initially penetrated into unrefrozen rubble. From the temperature versus depth profiles, the position of the freezing front could be determined (see fig 7), and from successive profiles the growth rate of the refrozen layer was calculated. For sea ice, accumulated degree days versus the ice thickness squared is a linear relationship (Parker, 1987). By May 2 about 2900 degree days had accumulated since the rubble formation and the refrozen layer was 3 m thick in the valley and 3.85 m thick under the sail with averaged growth rates of 1.7 cm/day and 2.7 cm/day respectively. The temperature versus depth profiles also show the thermal gradients above the freezing front and this enables one to calculate the rate of heat flow. From this it was calculated that only 12% of the unfrozen rubble keel was liquid water.

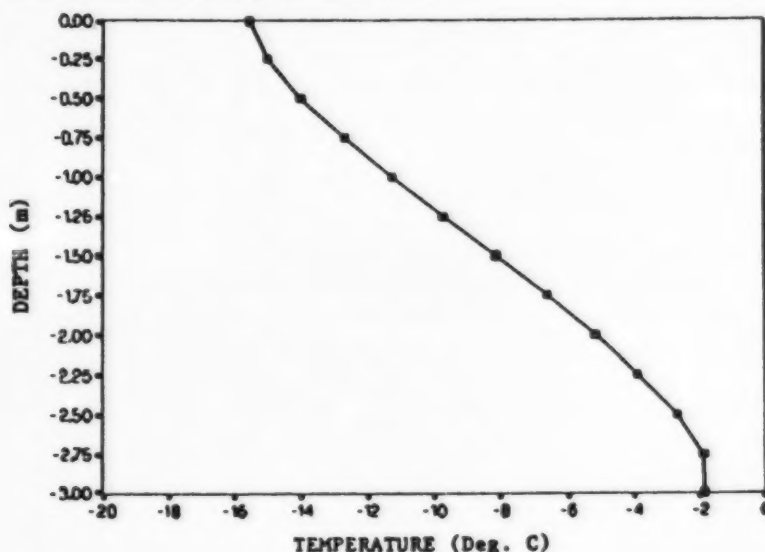


fig 7 Temperature versus depth profile from the short thermocouple array, midnight day 83-84.

9.0 RUBBLE PROFILE DATA

The surface of the rubble field consists of an irregular series of sails and valleys (see fig 8). A total of 89 ice rubble elevations were measured along 7 survey lines covering a combined distance of 540 m. The average height of the 27 sails surveyed was 3.8 m and the maximum observed (not along survey lines) sail height was 9 m.

Eight holes were drilled to establish the rubble thickness. This was

done to the southeast of the CRI and started on the floating, broken and uneven ice (disturbed zone) adjacent to the grounded rubble. The average thickness of the disturbed zone ice was 3.3 m (5 holes) and drilling into the rubble established that the rubble was grounded, even under a valley.

In April the rubble iceblock thickness was measured at various distances from the CRI. The thicknesses increased from 0.2 m, 10 m from the CRI, to 0.75 m at a distance of 75 m from the CRI.

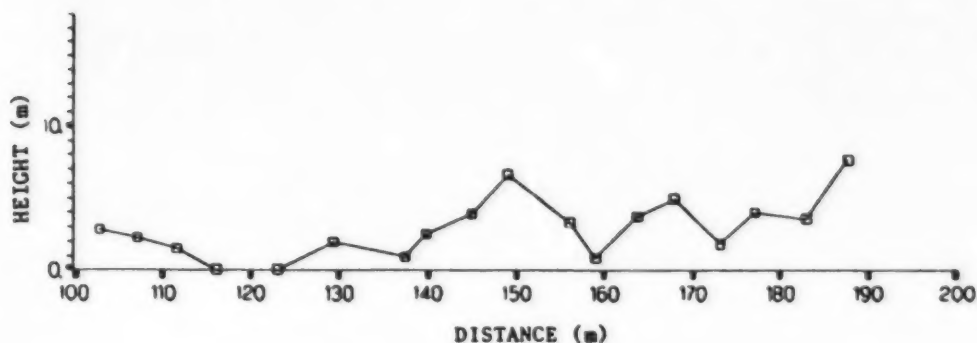


Fig 8 East survey line # 2 carried out to the south east of the CRI.

10.0 CONCLUSIONS

- 1) The CRI and ice rubble field provide useful platforms for studying force transmission through ice rubble, and large scale ice indentation.
- 2) Readings from the two sizes of pressure panel on the CRI clearly show that peak effective ice pressure increases with smaller contact area.
- 3) Thermally induced sea ice movements can cause significant ice loads.
- 4) Substantial pressure decrease after the formation of grounded rubble indicates that this protects the CRI.
- 5) A rapidly formed refrozen layer exists in the rubble and this should be accounted for in any theoretical models.
- 6) The refrozen layer was thickest under the sail, suggesting that despite the insulation provided by the sail, reduced rubble porosity under the sail allows greater refrozen thickness with less heat loss.
- 7) 0.2 m thick ice formed grounded rubble piles in 9 m deep water.

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